Measuring Transverse Quark Polarization with Spin Dependent Fragmentation Functions at \[ \text{and} \]

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Motivation: Measuring Transversity of the Nucleon
- Transversity
- Need for transverse spin dependent fragmentation functions for quark polarimetry

Transverse spin dependent Fragmentation Function measurement in $e^+e^-$ annihilation at Belle
- The Belle Experiment
- Recent Results for di-Hadron Interference Fragmentation Function
- Extraction of Transversity

Outlook
- Future Fragmentation Function measurements at Belle I+II
Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

- QCD successful in describing high energy reactions
- **BUT** No consistent description of hadronic sector
  - → No consistent description of fundamental bound state of the theory
  - QCD binding energy: most of the visible mass in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe.
Motivation for Studying Spin Proton Structure & Quantum Chromo Dynamics

- **QCD successful in describing high energy reactions**
- **BUT** No consistent description of hadronic sector
  - → No consistent description of fundamental bound state of the theory: proton
  - QCD binding energy: most of the visible energy in the universe
  - Spin is fundamental Quantum Number: What role does it play? Use transverse spin as precision probe
- **Compare to QED:**
  - Bound state: QED: atom
  - Stringent tests of QED from study of **spin** structure of hydrogen
    - Lamb shift (Nobel prize 1955)
  - → Atomic physics, QCD?
Inclusive polarized deep inelastic scattering (DIS)

\[ \sigma_{1/2} \sim \sum_i e_i^2 q_i^+ \]

\[ \sigma_{3/2} \sim \sum_i e_i^2 q_i^- \]
Probes to Study Polarized Proton Structure

Semi-Inclusive polarized deep inelastic scattering (DIS)

Fragmentation Process:
Outgoing quark forms hadrons
Probes to Study Polarized Proton Structure

(semi) Inclusive polarized deep inelastic scattering (DIS)

\[ \sigma_{1/2} \sim \sum_i e_i^2 q_i^+ \]

\[ \sigma_{3/2} \sim \sum_i e_i^2 q_i^- \]

polarized pp scattering

Hard Scattering Process

Dominates at RHIC
The three leading order, collinear PDFs

**unpolarized PDF**
quark with momentum $x = p_{\text{quark}} / p_{\text{proton}}$ in a nucleon

*well known – unpolarized DIS*

**helicity PDF**
quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon

*known – polarized DIS*

**transversity PDF**
quark with spin parallel to the nucleon spin in a transversely polarized nucleon

*Helicity – transversity: measurement of the nonzero angular momentum components in the protons wavefunction*

*chiral odd, poorly known*

*Cannot be measured inclusively*
Current Status of Distribution Functions

}\begin{align*}
f_1 &= \bullet \\
F_2 &\propto \sum_q e^q f_1^q \\
\end{align*}
Current Status of Distribution Functions

Unpolarized

Longitudinally Polarized

\[ F_2 \propto \sum_q x e_q^2 f_1^q \]

\[ g_1 \propto \sum_q e_q^2 g_1^q \]
**Current Status of Distribution Functions**

Unpolarized

\[ f_1 = \begin{array}{c} \text{Unpolarized} \end{array} \]

Longitudinally Polarized

\[ g_1 = \begin{array}{c} \text{Longitudinally Polarized} \end{array} \]

Transversely Polarized

\[ h_1 = \begin{array}{c} \text{Transversely Polarized} \end{array} \]

\[
F_2 \propto \sum_q x e_q^2 f_1^q
\]

\[
g_1 \propto \sum_q e_q^2 g_1^q
\]

\[
h_1 \propto \sum_q e_q^2 h_1^q \cdot H_1^q(z)
\]

Chiral odd - cannot be measured inclusively
Current Status of Distribution Functions

Unpolarized

$$f_1 = \bullet$$

Longitudinally Polarized

$$g_1 = \rightarrow \leftarrow$$

Transversely Polarized

$$h_1 = \rightarrow \leftarrow$$

$$F_2 \propto \sum_q x e_q^2 f_1 q$$

$$g_1 \propto \sum_q e_q^2 g_1^q$$
Transversity:

Why is \( \uparrow \rightarrow \downarrow \) so hard to measure?

- Naïve picture: leptonic probe too ‘fast’ to be sensitive to transverse polarization
Why is $\gamma$ so hard to measure?

Probability of finding $\uparrow$ quark

Probability of finding $\downarrow$ quark
Handbag Diagrams

Optical Theorem:

\[ \sigma = -Im(A_{\text{forward scattering}}) \]
Transversity is Chiral Odd

Transversity base:

- **Helicity base**: chiral odd
- Needs chiral odd partner $\rightarrow$ Fragmentation Function
- Does not couple to gluons $\Rightarrow$ different QCD evolution than $g_1(x)$
- Dominated by Valence Region
Importance of Transversity

\[ \frac{1}{2} = \frac{1}{2} \sum_{q,q} \int dx h_q(x) + \sum_{q,q,\bar{q}} \langle L_{st} \rangle \]

Baker, Leader, Trueman: Transverse Polarization Sum Rule

Only way to access tensor charge: \( \langle |\sigma^{\mu\nu}| \rangle = \int dx (h_q(x) - h_{\bar{q}}(x)) \) = \( g_T \)

- **Tensor charge** \( g_T \)** can come from lattice and experiment
  - Parton distributions on the light-cone \( \rightarrow \) compare moments
- Allows first order calculations connection to experiment
- Other quantities from lattice: Quark orbital momentum etc
Chiral odd Fragmentation Functions

Collins effect

$H'_1$ : Collins FF

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$H'_1$ : Collins FF
Chiral odd FFs

Interference Fragmentation Function

\((\pi^- \pi^+)\)

\(L_{z-1}\)

s-wave

\(\gamma^*\)

\(H\)

\(n\)

\(q\)

\(\rho\)

\(L_z\)

p-wave

\(\gamma^*\)
Quark Polarimetry with Interference FF in Quark Fragmentation

\[ \vec{k} \]
\[ \vec{s}_q \]
\[ \vec{R} \]
\[ \vec{R}_T \]
\[ z_{\text{pair}} = \frac{2E_{\text{pair}}}{\sqrt{s}} \]
\[ m \]

: quark momentum
: quark spin
: momentum difference \( \vec{p}_{h1} - \vec{p}_{h2} \)
: transverse hadron momentum difference
\[ = \frac{E_{\text{pair}}}{E_q} \]
: relative hadron pair momentum
: hadron pair invariant mass

**Interference Fragmentation Function:**
Fragmentation of a transversely polarized quark \( q \) into two spin-less hadron \( h1, h2 \) carries an azimuthal dependence:

\[ \propto (\vec{k} \times \vec{R}_T) \cdot \vec{s}_q \]
\[ \propto \sin \phi_{RS} \]
Transversity from di-Hadron SSA

\[ p+p \text{ c.m.s.} = \text{lab frame} \]
\[ \vec{P}_A, \vec{P}_B : \text{momenta of protons} \]
\[ \vec{P}_{h1}, \vec{P}_{h2} : \text{momenta of hadrons} \]
\[ \vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2} \]
\[ \vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2}) / 2 \]
\[ \vec{S}_B : \text{proton spin orientation} \]

\[ pp^\uparrow \rightarrow hhX \]

\[ d\sigma_{UT} = 2 |\vec{P}_{C\perp}| \sum_{a,b,c,d} \left| \frac{R_c}{M_C} \right| |S_{BT}| \sin (\phi_{SB} - \phi_{RC}) \int \frac{dx_adx_b}{16\pi z_c} f_1^a(x_a) h_1^b(x_b) \frac{d\Delta\sigma_{ab\uparrow \rightarrow c\downarrow}}{dt} H_1^{ac}(z_c, M_C^2) \]

Unpolarized quark distribution
Known from DIS

Transversity to be extracted

Hard scattering cross section from pQCD

IFF + Di-hadron FF measured in e+e at Belle-

\[ \phi_R : \text{from scattering plane to hadron plane} \]
\[ \phi_S : \text{from polarization vector to scattering plane} \]
NEW: STAR shows significant Signal!

- First significant signal of transversity in polarized proton collisions

\[ A_{UT} \propto h_1 \cdot H_<^{1} \]
Measurements of Fragmentation Functions in e⁺e⁻ at Belle

- KEK-B: asymmetric e⁺ (3.5 GeV) e⁻ (8 GeV) collider:
  - $\sqrt{s} = 10.58$ GeV, e⁺e⁻ → Y(4S) → B $\bar{B}$
  - $\sqrt{s} = 10.52$ GeV, e⁺e⁻ → qqbar (u,d,s,c) ‘continuum’
- ideal detector for high precision measurements:
  - tracking acceptance $\theta$ [17°;150°]: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID
- Available data:
  ~1.8 *10⁹ events at 10.58 GeV,
  ~220 *10⁶ events at 10.52 GeV
Belle Detector

SC solenoid
1.5T

Csl(Tl) 16X₀

TOF counter

8GeV e⁻

3.5GeV e⁺

Aerogel Cherenkov cnt.
n=1.015~1.030

Tracking + dE/dx
small cell + He/C₂H₆

μ / Kₗ detection
14/15 lyr. RPC+Fe

Si vtx. det.
3 lyr. DSSD

Large acceptance, good tracking and particle identification!
dE/dx (CDC)  
TOF (only Barrel)  
Barrel ACC  
Endcap ACC  

$\Delta dE/dX \sim 5\%$  
$\Delta T \sim 100\, \text{ps} \, (r = 125\, \text{cm})$  
n = 1.010 – 1.028  
n = 1.030  
(only flavor tagging)  

$p \, (\text{GeV/c})$  

$\log_{10}(p \, (\text{GeV/c}))$  

$D^{*+} \rightarrow D^0\pi^+$  
$\rightarrow K^-\pi^+$  

$\pi$ track  
$K$ track
Measuring Light Quark Fragmentation Functions on the \( \Upsilon(4S) \) Resonance

- small B contribution (<1%) in high thrust sample
- >75% of X-section continuum under \( \Upsilon(4S) \) resonance
- \( \sim 100 \text{ fb}^{-1} \Rightarrow \sim 1000 \text{ fb}^{-1} \)

\[ e^+e^- \rightarrow q\bar{q}, \, q \in uds \]

\[ e^+e^- \rightarrow c\bar{c} \]

\[
\text{Thrust} \colon T = \frac{\sum_{i} |p_i \cdot \hat{n}|}{\sum_{i} |p_i|}
\]
How to Measure Spin Dependent Fragmentation Functions in unpolarized $e^+ e^-$
Measuring transverse spin dependent di-Hadron Correlations
In unpolarized $e^+e^-$ Annihilation into Quarks

Interference effect in $e^+e^-$ quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements!

**Experimental requirements:**
- Small asymmetries $\Rightarrow$ very large data sample!
- Good particle ID to high momenta.
- Hermetic detector

$$A \propto H_1(z_1, m_1)\overline{H}_1(z_2, m_2) \cos(\phi_1 + \phi_2)$$
Interference Fragmentation Function from di-Hadron Pair Correlations

- $e^+e^- \rightarrow (\pi^+\pi^-)_{\text{jet}_1}(\pi^+\pi^-)_{\text{jet}_2}X$
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1 + \varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Early work by Collins, Heppelmann, Ladinsky [NPB420(1994)]

Model predictions by:
- Jaffe et al. [PRL 80, (1998)]
- Radici et al. [PRD 65, (2002)]

$$A \propto H_1^\perp(z_1, m_1)\overline{H}_1^\perp(z_2, m_2) \cos(\varphi_1 + \varphi_2)$$
Transverse Spin Dependent FFs: Cuts and Binning

- Full off-resonance and on-resonance data (7-55): ~73 fb\(^{-1}\) + 588 fb\(^{-1}\)
- Visible energy >7GeV, exclusion of \(\tau \rightarrow \pi^- \pi^+ \pi^- \nu_\tau\)
- PID: Purities in for di-pion pairs > 90%
- Same Hemisphere cut within pair (\(\pi^+ \pi^-\)), opposite hemisphere between pairs
- All 4 hadrons in barrel region: \(-0.6 < \cos(\theta) < 0.9\)
- Thrust axis in central area: cosine of thrust axis around beam <0.75
- Thrust > 0.8 to remove B-events \(\rightarrow < 1\%\) B events in sample
- \(z_{\text{had1, had2}} > 0.1\)
- \(z_1 = z_{\text{had1}} + z_{\text{had2}}\) and \(z_2\) binning
- \(m_{\pi\pi_1}\) and \(m_{\pi\pi_2}\) binning
- \(m_{\pi\pi_1, z_1}\) binning

T-spin projection: \(\sin(\theta)^2 / 1 + \cos(\theta)^2\)
Asymmetry extraction

- Build normalized yields:
  \[ \frac{N(\phi_1 + \phi_2)}{\langle N \rangle}, \]

- Fit with:
  \[ a_{12} \cos(\phi_1 + \phi_2) + b_{12} \]
  or
  \[ a_{12} \cos(\phi_1 + \phi_2) + b_{12} + c_{12} \cos 2(\phi_1 + \phi_2) + d_{12} \sin(\phi_1 + \phi_2) \]

Amplitude \( a_{12} \) directly measures (IFF) \( \times \) (-IFF) (no double ratios)
Zero tests: MC

- A small asymmetry seen due to acceptance effect
- Mostly appearing at boundary of acceptance
- Opening cut in CMS of 0.8 (~37 degrees) reduces acceptance effect to the sub-per-mille level

Energy flow with opening cut of 0.8
First measurement of Interference Fragmentation Function

\[ a_{12} \propto H_{1} \cdot \bar{H}_{1} \]
(m₁ x z₁) Binning

- 0.25 GeV/c² < m₁ < 0.40 GeV/c²
- 0.40 GeV/c² < m₁ < 0.50 GeV/c²
- 0.50 GeV/c² < m₁ < 0.62 GeV/c²
- 0.62 GeV/c² < m₁ < 0.77 GeV/c²
- 0.77 GeV/c² < m₁ < 0.90 GeV/c²
- 0.90 GeV/c² < m₁ < 1.10 GeV/c²
- 1.10 GeV/c² < m₁ < 1.50 GeV/c²
- 1.50 GeV/c² < m₁ < 2.00 GeV/c²
Comparison to theory predictions

- Mass dependence: Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)
- Z dependence: Rising behavior steeper

Red line: theory prediction + uncertainties
Blue points: data

- Mass dependence: Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)
- Z dependence: Rising behavior steeper
Subprocess contributions (MC)

8x8 $m_1$, $m_2$ binning

tau contribution (only significant at high z)
charged B (<5%, mostly at higher mass)
Neutral B (<2%)
charm (20-60%, mostly at lower z)
uds (main contribution)
Subprocess contributions (MC)

9x9 $z_1$, $z_2$ binning

- Tau contribution (only significant at high $z$)
- Charged $B (<5\%$, mostly at higher mass$)$
- Neutral $B$ ($<2\%$)
- Charm ($20-60\%$, mostly at lower $z$)
- UDS (main contribution)
COMPASS 2004 Setup

- High energy beam
- Large angular acceptance
- Broad kinematical range

2002-2004:
- 6LiD (Deuteron)  
  - dilution factor $f = 0.38$  
  - polarization $PT = 50\%$

2005:
- NH3 (proton)
  - 3 target cells with opposite polarization, 90% polarization, 16% dilution

Sigma terms:
\[ \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} (\phi^S - \phi^R) = A_{UT} \cdot \sin(\phi^S - \phi^R) \]

- $A_{UT} \propto h_1 \cdot H^1$

Graph showing $A_{UT}$ vs. $x$ and $M_{inv}$.
Measurement at Belle leads to first point by point extraction of Transversity

Future Plans at Star/Belle:
Better sensitivity to d transversity
From $\pi^0/\pi^+/-$ combinations
Increase x range

Is Soffer Bound violated?
$h(x) < |f(x) + g(x)|/2$

$A_{UT} \propto h_1 \cdot H^<_1$

M. Radici at FF workshop, RIKEN, 11/2012

$\alpha_{12} \propto H^<_1 \cdot H^<_1$
Jet Handedness

\[ \text{Handedness: } \frac{(\vec{k}_+ \times \vec{k}_-) \cdot \vec{t}}{|\vec{k}_+| \cdot |\vec{k}_-|} \Rightarrow \text{L/R} \]

\[ = \sin \Phi > 0 \]

\[ \text{Jet handedness: } \frac{N_R - N_L}{N_R + N_L} \]
Handedness Correlations

- Handedness Correlations expected to be zero in factorized approach
- Non-zero asymmetries predicted in factorized approach for azimuthal asymmetries sensitive to $G_{1}^{\perp}$
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries

Jet handedness:

$$\text{handedness: } \frac{N_R - N_L}{N_R + N_L}$$

C:

$$\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}$$
**Handedness Correlations**

- Handedness Correlations expected to be zero in factorized approach
- Non-zero asymmetries predicted in factorized approach for azimutal asymmetries sensitive to $G_{1}^{\perp}$
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries

\[
\text{Handedness: } \frac{(k_+ \times k_-) \cdot \hat{t}}{|k_+| |k_-|} > 0 \quad \Rightarrow \quad \text{L/R}
\]

[Diagram showing thrust direction and particle interactions]

Jet handedness:

\[
\text{handedness: } \frac{N_R - N_L}{N_R + N_L}
\]

C:

\[
\frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}}
\]
Handedness Correlations

- Handedness Correlations expected to be zero in factorized approach
- Non-zero asymmetries predicted in factorized approach for azimuthal asymmetries sensitive to $G_{1}^{\perp}$
- Several suggestions how interactions with QCD vacuum can lead to non-zero asymmetries
- SLD: Upper bound from 90k hadronic Z events: 7%

\[ \text{Handedness: } \frac{(\overrightarrow{k}_+ \times \overrightarrow{k}_-) \cdot \hat{t}}{|\overrightarrow{k}_+| |\overrightarrow{k}_-|} > 0 \implies \text{L/R} \]

Jet

\[ \text{handedness: } \frac{N_R - N_L}{N_R + N_L} \]

\[ C: \frac{N_{RL} + N_{LR} - N_{RR} - N_{LL}}{N_{RL} + N_{LR} + N_{RR} + N_{LL}} \]

Correlation from MC zero as expected
Unpolarized Fragmentation Functions

- Precise knowledge of upol. FFs necessary for virtually all SIDIS measurements

Lack of data at high $z$, lower CMS

- $\pi^0$, $\eta$ fragmentation function under way
- In particular important at RHIC
**KEKB/Belle → SuperKEKB, upgrade (2010–2015)**

- **Aim:** super-high luminosity $\sim 10^{36} \text{ cm}^{-2}\text{s}^{-1}$ (~40x KEK/Belle)
  - Will allow $p_T$ dependent extraction of fragmentation functions
- **Upgrades of Accelerator (Microbeams + Higher Currents) and Detector**
  - Significant US contribution

[Diagram showing modifications to the KEKB/Belle facility for SuperKEKB upgrade]

[Link: http://belle2.kek.jp]
Belle II Detector at SuperKEKB (L x 40) and IU contributions to Barrel Particle ID

- Barrel PID instrumental for fragmentation function measurements

EM Calorimeter:
CsI(Tl), waveform sampling (barrel)
Pure CsI + waveform sampling (end-caps)

Particle Identification
Time-of-Propagation counter (barrel)
Active HV Divider board for MCP-PMT
Validation of FPGA code of iTOP

Vertex Detector
2 layers DEPFET + 4 layers DSSD

Vertex resolution improved by order of magnitude:
Separate charm/uds

- RPC test stand at IU to test electronics: E. Zarndt, S. Arnold

K_L and muon detector:
Resistive Plate Counter (barrel outer layers)
Scintillator + WLSF + MPPC (end-caps, inner 2 barrel layers)

RPC Front End Electronics, Concentrator boards for barrel and endcap scintillator layers

- e- (7GeV)
- e+ (4GeV)
Belle II Status
Summary

- Breakthrough Measurements of Proton Structure underway: How does QCD work inside the Nucleon?
- Di-hadron Correlations best way to access transversity in p+p, SIDIS needed to describe spin structure of the proton, derive tensor charge
- Corresponding Fragmentation Functions measured at Belle
  - IFF, Collins in Pions, Kaons (underway), spin averaged single, di-hadron Fragmentation functions,

**Outlook**
- **Belle II**: Continuation of FF measurements with improved Kaon ID and vertex reconstruction
- Use charm rejection
- Probe QCD vacuum polarization
- Measure transverse momentum dependent spin dependent and spin averaged fragmentation functions
- Precision measurements at Belle (II) crucial for forthcoming measurements at BNL, Jlab, CERN
THANK YOU!

Questions?
• Backup
12 GeV JLab

- Add 5 cryomodules
- 20 cryomodules
- Add arc
- Add Hall D (and beam line)
- CHL-2
- 20 cryomodules

Enhance equipment in existing halls

Upgrade magnets and power supplies
12 GeV JLab

Add 5 cryomodules

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CHL-2

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High Luminosity Access to valence quarks

DIS up to $x \approx 0.8$

SIDIS, $x \approx 0.55$
**Di-hadron Correlations at CLAS**

- Di-hadron correlations at CLAS to extract higher twist distribution functions and transversity (with new target)
- Need for $\pi K$ IFF to exclude target Fragmentation (Belle!)

Plots from H. Avakian

Dihadron sample defined by SIDIS cuts+$x_F>0$ (CFR) for both hadrons

$X_F^1$ - Distribution of $x_F$ vs. $x_F$

$X_F^2$ - Momentum in the CM frame
Transversity at high $x$ from polarized He$^3$ at SoLID with 12 GeV Upgrade at JLab

- Precise measurement of $p_T$ dependent Collins effect
  - Needs precise measurement of Collins and spin averaged $p_T$ dependent fragmentation functions
Collins Extraction of Transversity: model dependence from Transverse Momentum Dependences!

\[ A_{UT}^{Collins} = \sum_q e_q^2 \int d\phi_S d\phi_h d^2 k_\perp h(x, k_\perp) \frac{d(\Delta\sigma)}{dy} H_{1,q}^\perp(z, p_\perp) \sin(\phi_S + \phi + \phi_h) \sin(\phi_S + \phi) \]

\[ \sum_q e_q^2 \int d\phi_S d\phi_h d^2 k_\perp q(x, k_\perp) \frac{d(\Delta\sigma)}{dy} D_q^h(z, p_\perp) \]

\( k_\perp \) transverse quark momentum in nucleon
\( p_\perp \) transverse hadron momentum in fragmentation

The transverse momentum dependencies are still unknown
Need \( p_T \) dependent FFs from Belle to extract transversity and test TMD framework

Anselmino, Boglione, D’Alesio, Kotzinian, Murgia, Prokudin, Turk